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Hybrid adsorption cooling systems–An overview

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ABSTRACT

With sharp rising global energy demand posing a rapid development in sustainable cooling systems is required. Hybrid adsorption cooling cycle is considered as one of the sustainable cooling systems. The present study introduces a survey of hybrid adsorption cooling systems in order to stand on its fact and clarify the future trend. The survey sectioned the hybrid adsorption systems into three sections; (i) assisted technology, (ii) application, and (iii) heat source type. The hybrid system which uses vapor compression with adsorption employing activated carbon/CO_2 pair was found to have the highest value of the coefficient of performance (COP). On the contrary, vapor compression-hybrid cooling system using activated carbon/R134a as the adsorbent/refrigerant pair has the lowest COP value and substantial research development and demonstration (RD&D) is required to meet the global challenge of energy conservation.

Contents

1. Introduction

The earliest record of the phenomenon of adsorption refrigeration is the ammonia adsorption on AgCl, which was discovered by Faraday in 1848 [1,2]. In the 1920s, Hulse [3] suggested a refrigerator which utilized silica gel/SO_2 as a working pair and reached the evaporation temperature of about $-12\,^{\circ}C$, to store food on trains. Since 1930, the technology of vapor mechanical compression refrigeration has developed quickly, and adsorption refrigeration could no longer compete with those systems. From the oil crisis of the 1970s, attention turned again to adsorption systems for their energy saving potential. There are two types of adsorption refrigeration working pairs: (1) physical adsorption working pairs, such as zeolite/water, activated carbon/methanol, activated carbon/ammonia and silica gel/water; (2) chemical adsorption working pairs, which are mainly metal hydride/hydrogen and metal chloride (e.g. $CaCl_2$, LiCl, etc.)/ammonia. The force between metal chlorides and ammonia is complexation force where the reaction between calcium chloride can be written as

$$CaCl_2.n_1\ NH_3+n_2\Delta Hr\leftrightarrow CaCl_2.(n_1-n_2)\ NH_3+n_2NH_3$$

Where ΔH_r is the reaction enthalpy (J/mol), the numbers of $n_1$and n_2 could be 2, 4 and 8.

There are composite adsorbents (e.g. expanded porous graphite and $CaCl_2$, thus the thermal conductivity could be greatly enhanced) and the compound adsorbents (e.g. activated carbon

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and $CaCl_2$ in which both physical and chemical adsorption existed when ammonia is used as refrigerant) [2,4,5].

Compared with absorption refrigeration systems, which can also be powered by low-grade heat, the advantages of solid sorption refrigeration are as follows [4]:

(1) Adsorption cooling systems can be powered by heat sources as low as 50 °C but in absorption systems the source should be at least at 70 °C.
(2) Adsorption refrigeration systems are suitable for conditions with serious vibration, such as in fishing boats and locomotives, but absorption systems, due to the fact that the absorbent is in liquid state, have problems because the absorbent can flow from the generator to the evaporator or from the absorber to the condenser. When such a displacement of the absorbent occurs, the refrigerant became polluted and the system cannot work normally.
(3) Adsorption systems can be much simpler than absorption systems. For example, in the NH_3–H_2O absorption system, rectifier equipment must be coupled to the system because the boiling point of water is similar to that of ammonia.

In order to lessen the ozone depletion due to CFCs, reduce the large energy consumption, and protect the environment, many refrigeration cycles driven by thermal energy, e.g. absorption, adsorption, and ejector cycles, as the substitutes for vapor compression cycle have become of interest again [6–17]. Adsorption cooling systems have received a lot of attention due to their effective cold production based on waste heat or solar energy utilization. Adsorption cooling systems are environmentally friendly and they can utilize the low-grade waste heat or renewable energy as the main driving energy and thus have a large energy saving potential [18].

Along with the development of adsorption refrigeration technology and its industrialization and commercialization, adsorption refrigeration is turning into a kind of energy-saving, environment-friendly refrigeration technologies. Although solid adsorption refrigeration has received much attention from most of the refrigeration companies and laboratories around the world, some of the main disadvantages such as small refrigeration capacity per unit mass of adsorbent, have become obstacles for the real mass production of the system. Treatment of adsorbent to increase its adsorption capacity on a refrigerant could increase the refrigeration capacity of adsorbent per unit mass and also the COP (coefficient of performance) of the cycle. Besides, several investigations had attempted to further improve (hybrid) the performance of the existing solar refrigerators, by combining the basic adsorption cycle with other refrigeration cycles, as well as, in designing a dual system [19].

Over several decades, multi-production hybrid solar energy systems have been introduced for many applications with proven environmental and economic benefits [20–23]. Many investigations have been carried out on the feasibility and energy-saving potential of hybrid cooling systems.

In this study we will review the researches which use the adsorption cooling technology in cooperation with the other technologies. The study will introduce a layout for the experimental and simulated adsorption hybrid systems in order to know its benefit. The study will focus on the principle of working for these systems and the COP.

2. Adsorption hybrid systems

Hybrid adsorption cooling systems are more viable than the stand alone adsorption cooling systems. Hybrid adsorption cooling system is a mixture of different techniques in one system to improve its efficiency. This mixture could be by using different cooling technologies like using a compression cycle with the adsorption cycle. It also could be in the application of the system like using the waste heat of the adsorption cooling system as a heat source for some domestic applications. And it could be in heat source like using solar energy with an electrical heater to drive the adsorption cooling system.

The hybrid adsorption systems will be divided into three branches. First according to cooling technologies, second according to its employment and finally according to the heat source. The study will concentrate on the hybrid adsorption systems which participants in cooling technologies.

2.1. Assistant cooling technologies

Ma et al. [24] derived the performance analysis for a hybrid air conditioning system of a green building. A 150 m^2 solar collector was used to power two 10 kW adsorption chillers, a vapor compression heat pump was used to cool air in the evaporating end while the heat of condensing at about 80 °C was fully used to regenerate a liquid desiccant dehumidification system. The sensible cooling to the air was treated mainly by solar adsorption cooling and vapor compression cooling and the latent heat was treated by the liquid desiccant dehumidification system with regeneration from the condensing heat of the heat pump. A schematic diagram for the system is shown in Fig. 1.

Vapor compression heat pump, in which chilled water with temperature of about 15 °C was produced from evaporator and hot water with temperature of above 65 °C was obtained from condenser simultaneously. The cooling was used to cool the supply air while the condensing heat was used to regenerate the liquid desiccant. Liquid desiccant dehumidification system was composed of dehumidifier, heat exchanger HE2 to recover energy and regenerator. In this liquid desiccant loop lithium bromide solution was used as liquid desiccant due to its high energy storage capacity of about 1000 MJ/m^3.

The results showed that the performance of this system was 44.5% higher than conventional vapor compression system at a latent load of 30% and this improving was achieved by 73.8% at a 42% latent load.

Banker et al. [25] studied the performance of mechanical and adsorption hybrid compression refrigeration cycles with HFC 134a.

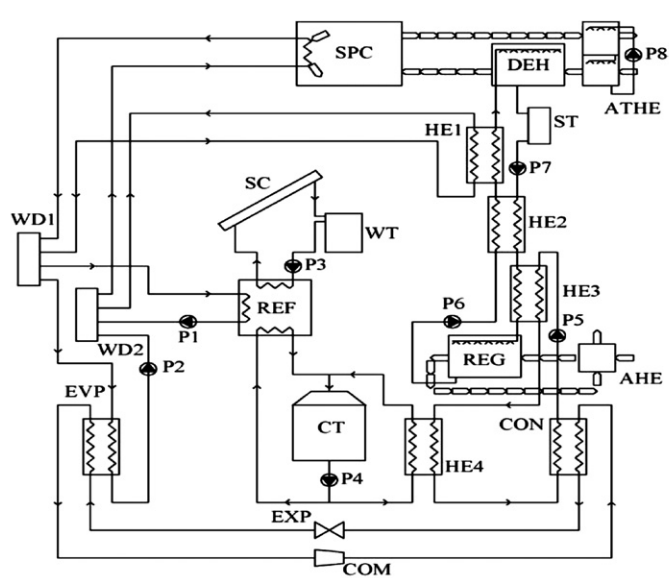


Fig. 1. Schematic diagram of hybrid air-conditioning system of green building [24]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The conventional mechanical compression was supplemented by thermal compression using a string of adsorption compressors. Activated carbon was the adsorbent for the thermal compression segment. Fig. 2 shows a schematic hybrid cycle where the adsorption provided the low stage compression. The refrigerant from evaporator was taken to the adsorption compressor, where it adsorbed by activated carbon at near condensation temperature. Then, it was desorbed where; the desorbed refrigerant vapor at nearly the waste heat source temperature was passed through the intercooler and then was drawn into a mechanical compressor for high stage compression. The rest of the refrigeration cycle followed the usual pattern. The other possibility was to use the mechanical compression for the lower stage as shown in Fig. 3.

The study showed that, almost 40% energy saving was realizable by carrying out a part of the compression in a thermal compressor compared to the case when the entire compression was carried out in a single-stage mechanical compressor.

Fong et al. [26] introduced a solar hybrid air-conditioning system for high temperature cooling in subtropical city. The solar hybrid air-conditioning system was benchmarked with the conventional vapor compression refrigeration for office use. Comparative study was conducted for the hybrid air-conditioning system worked with the three common types of chilled ceilings, namely the chilled panels, passive chilled beams and active chilled beams.

Fig. 4 shows a schematic diagram for the system with chilled panels/passive chilled beams and with active chilled beams. The system consisted of four sub-systems, solar energy collection, adsorption refrigeration, desiccant dehumidification and radiant ceiling cooling. The solar energy collection would supply chilled water for radiant ceiling cooling, which was used to handle the space cooling load. The latter was used to handle the ventilation load of the fresh outdoor air supplied to the indoor space. Whenever the solar thermal gains were not enough, auxiliary heating would be supplemented in order to effectively handle the required building cooling loads.

The chiller was sized based on a design entering desorption water temperature of 80 °C, entering cooling water temperature of 30 °C and entering chilled water temperature of 18 °C. The corresponding chiller capacities were 26 kW and 33 kW. The desiccant dehumidification cycle was used to fully handle the ventilation load from fresh air, as well as the space latent load, in order to prevent condensation on the surface of chilled ceiling equipment. A heating coil capacity of 6 kW was required. The design regeneration temperature was 80 °C. The capacity of auxiliary heater was 7 kW.

The study concluded that the system with either passive or active chilled beams could generally achieve the indoor design conditions. However, the yearly primary energy consumption with active chilled beams could be up to 36.1% more than that with passive chilled beams, so the option of passive chilled beams was more energy-efficient to work with the solar hybrid air-conditioning system. Through the solar hybrid air-conditioning system, it could provide a definite alternative to the places where air-conditioning was indispensable. Since the percentage of energy consumption of air-conditioning was substantial in office buildings, wider application of solar air-conditioning was a sustainable solution in the subtropical cities.

It was found that the proposed solar hybrid air-conditioning system was technically feasible through high temperature cooling. Among the three types of chilled ceilings, the passive chilled beams were the most energy-efficient option to work with the solar adsorption refrigeration for space conditioning in the subtropical city.

Brian and Levan [27] examined thermodynamically a compression-driven adsorption cooling cycle. The cycle was simulated for each of three different adsorbate/adsorbent pairs: CO_2/zeolite, CO_2/activated carbon, and ammonia/silica gel.

Two-bed system based on the design of Leppard was described. The condenser of a vapor compression heat pump and had been replaced by an adsorbing bed, as shown in Fig. 5. During the cooling stages of the cycle, a compressor drew the working fluid from the low temperature, desorbing bed, and passed it into the high temperature, adsorbing bed. The heat of desorption was removed from the thermal reservoir in contact with the low pressure bed. Following compression and adsorption in the high temperature bed, the heat of adsorption was released to a second thermal reservoir.

The COP of the system was found to be strongly influenced by both the heat capacity of the adsorbent and the shape of the isotherm. Results for the adsorption cycle suggested that production of cooling required a compression system capable of producing pressure ratios of at least 15. Simulations also indicated that given the same temperature raised, the ammonia/silica gel system provided a COP approximately 1/3 smaller than the condensation/evaporation system for ammonia.

A new combined adsorption–ejector refrigeration and heating hybrid system powered by solar energy had been proposed and simulated by Zhang and Wang [28]. The combined hybrid system consisted of two parts: heating system and cooling system as shown in Fig. 6, and used zeolite/water as a working pair.

The ejector and the adsorber were used instead of mechanical compressors to compress the refrigerant vapor from the evaporator to the condenser. In the daytime from a solar concentrator the adsorber of the heating system absorbed solar energy and desorbing

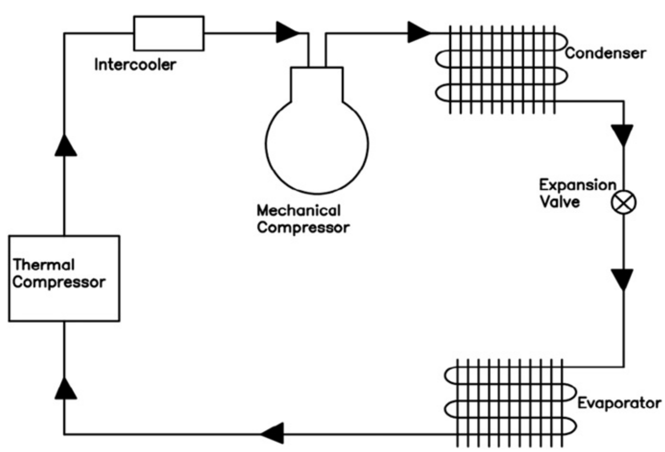


Fig. 2. Schematic diagram of adsorption+compressor hybrid refrigeration system [25].

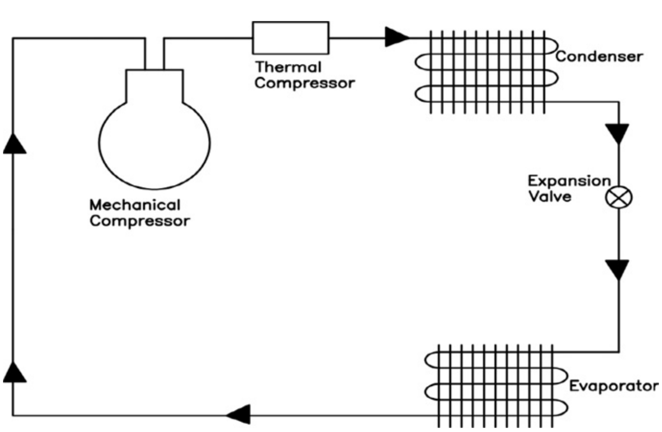


Fig. 3. Schematic diagram of reverse hybrid refrigeration system [25].

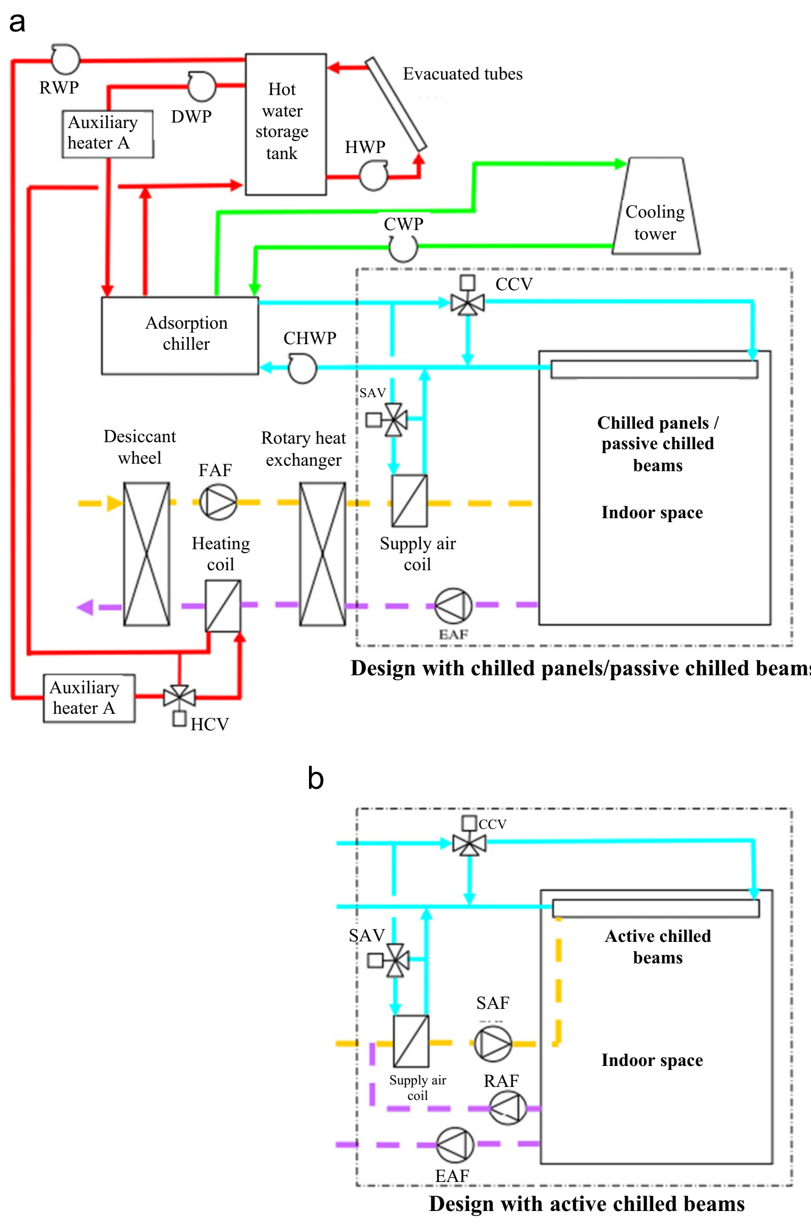


Fig. 4. Schematic diagram of solar hybrid air-conditioning system: (a) design with chilled panels/passive chilled beams, and (b) design with active chilled beams [26].

water from the zeolite. When the temperature and pressure in the adsorber reached certain values, the adsorber was connected to the ejector, and disconnected the adsorber from the evaporator.

Water vapor of high temperature and pressure from zeolite entered the ejector, and was accelerated in the convergent–divergent nozzle. At the exit of the nozzle, the primary flow reached a supersonic velocity and a lower pressure, and entered the water vapor from the evaporator to the suction chamber with the valve 3 opening. Mixing of the two streams began there with a uniform pressure, up to the inlet of the constant area section. The mixture was then compressed into the condenser by the diffuser, in which hypothetically the temperature and pressure of water vapor reached mid values, in the ideal process, and was cooled into liquid, then entered into the receiver, and finally returned to the evaporator by the throttle valve.

From the simulation results, the combined hybrid system could furnish 290 kg hot water at 45 °C with a heating COP of 0.55, and could refrigerate with a cooling COP of 0.1 in the daytime, with a COP of 0.23 in the night. So it could be concluded that the new combined cycle could raise the COP totally and could refrigerate in the daytime.

A novel combined cycle of a solar powered adsorption–ejection refrigeration system had been studied by Li et al. [29]. As shown in Fig. 7, it included two subsystems: the adsorption sub-system, which refrigerates at night time and the ejection subsystem, which refrigerates during the day. During the daytime, the vapor at high temperature and high pressure produced in generator and auxiliary heater entered the ejector and formed supersonic primary fluid at the exit of the nozzle. This enabled the entrainment of the secondary fluid from the evaporator. The secondary fluid subsequently mixed with the primary fluid in the mixing chamber of the ejector, and when flowing into the condenser, the mixed fluid condensed into liquid. This liquid was finally divided into two parts: one part went into the evaporator as in other cycles; the other was pumped back to the generator [30]. At the same time, the adsorber was heated up by solar energy. When the pressure in the adsorber rose to a certain value, the desorbed vapor then entered the generator as

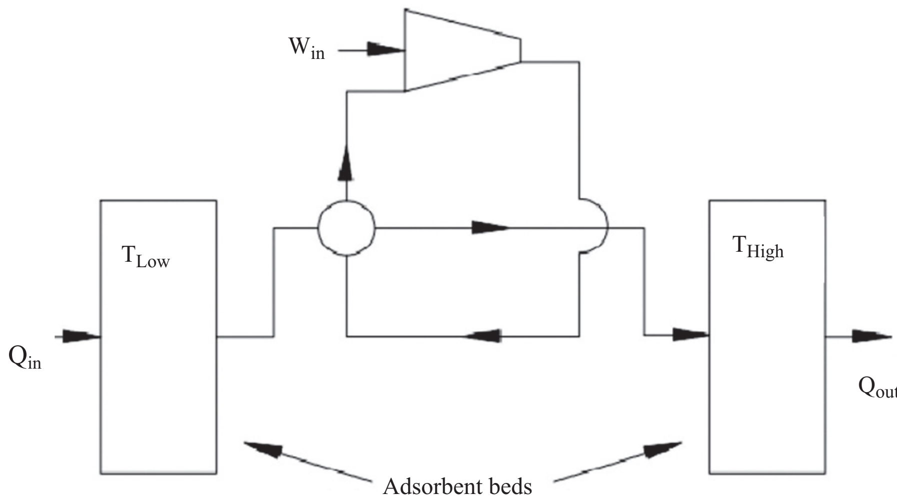


Fig. 5. Compressor-driven adsorption cooling cycle [27].

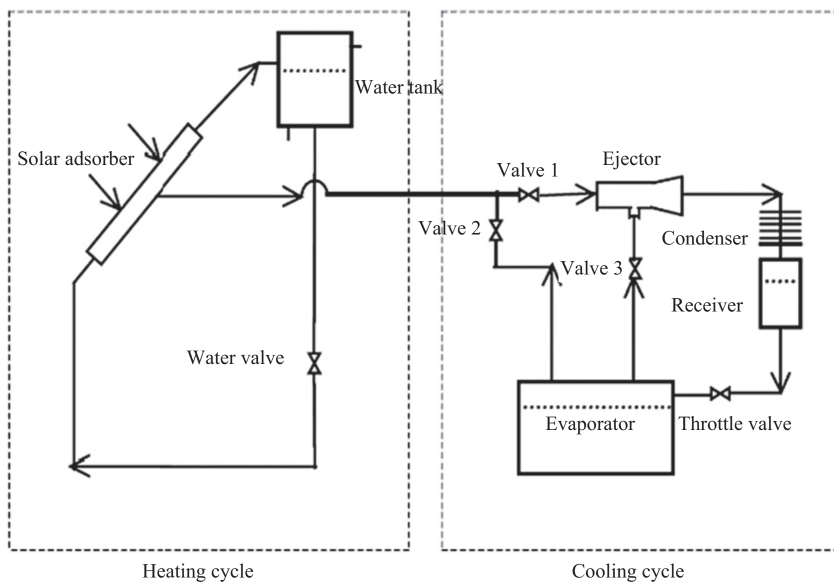


Fig. 6. Solar combined solid adsorption–ejector refrigeration and heating hybrid system [28].

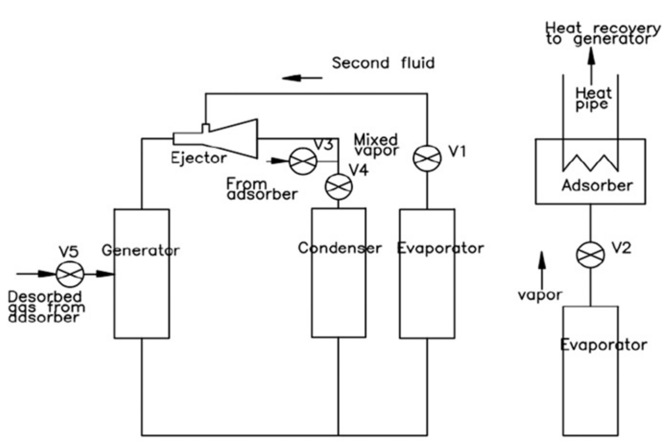


Fig. 7. Schematic of the ejection refrigeration and adsorption refrigeration systems [29].

the primary fluid for the ejection cycle. During night time, and when the temperature within the adsorber decreased to Ta_2, the adsorbent began to adsorb the refrigerant.

In order to recover the sensible heat and the heat of adsorption, a heat pipe was used. The recovered heat was applied to heat the refrigerant or thermal storage material in the generator for the ejection cycle at the next day. When thermal equilibrium was reached, the heat pipe will stop working, and then a heat exchanger (x_2) was needed to cool the adsorber further.

The main advantage of this system was to overcome the intermittence problem in solar-powered adsorption refrigeration, together with increasing the performance of the ejection system. It was reported that increasing the temperature or reducing pressure within the adsorbent bed, the COP of the ejection subsystem improved very slightly, but if much more adsorbent was used, a better result might be obtained.

Luo et al. [31], investigated a solar adsorption chiller used for grain depot cooling. This solar adsorption chiller consisted of four

subsystems, namely, a solar water heating unit with 49.4 m^2 solar collecting area, a silica gel/water adsorption chiller, a cooling tower and a fan coil unit. In order to achieve continuous refrigeration, two adsorption units were operated out-of-phase with mass recovery cycle in the adsorption chiller. Fig. 8 shows a schematic diagram for the system.

The solar water heating unit was utilized to produce hot water to drive the adsorption chiller. The cooling tower offered the cooling water to cool the condensers and adsorbers. The cooling production was transferred to a grain depot through a fan coil unit. A wind valve was employed to control the outlet air temperature of the fan coil unit.

The study showed that the adsorption chiller could run effectively when the hot water temperature was above 65 °C. The adsorption chiller could be operated with a two adsorber continuous refrigeration cycle with mass recovery. One-minute mass recovery process improved the COP and cooling power of the adsorption chiller effectively. With a daily solar radiation of 16–21 MJ/m^2 the solar adsorption chiller provided 6.5–8.5 h of cooling with an average cooling power of 3.2–4.4 kW and with a solar cooling COP of about 0.1–0.13.

Dai et al. [32], studied a solar powered solid adsorption–desiccant cooling system used for grain storage. The hybrid system combined the technologies of rotary desiccant dehumidification and solid adsorption refrigeration. The hybrid solar cooling system was configured primarily by three subsystems, namely: solid intermittent adsorption refrigeration; desiccant dehumidification; and cold storage, as shown in Fig. 9. Solid adsorption refrigeration included a solar adsorption bed, condenser, receiver and evaporator.

Desiccant dehumidification consisted of a rotary desiccant wheel, a regenerative heater, and a thermal storage heat exchanger. In cold storage, the grain itself was used as the cold storage material where a fan-coil unit was applied to supply cold air into the grain packs. Cooling water flowing in the condenser came from the water recycling in the evaporative cooler. Here, activated carbon/methanol was selected as a working pair. The desorption temperatures for both desiccant material and activated carbon/methanol was within the range of 80–100 °C.

During the day the adsorption bed received solar irradiation and turned it into thermal energy, which led to a rise in temperature. The desorption process of methanol started when the pressure of the bed was higher than that of the condenser, which was determined by the temperature of cooling water. The desorbed methanol turned into liquid state from vapor, and was collected in the receiver. At night, natural convection and irradiation cool the adsorption bed and caused the pressure to drop in the bed.

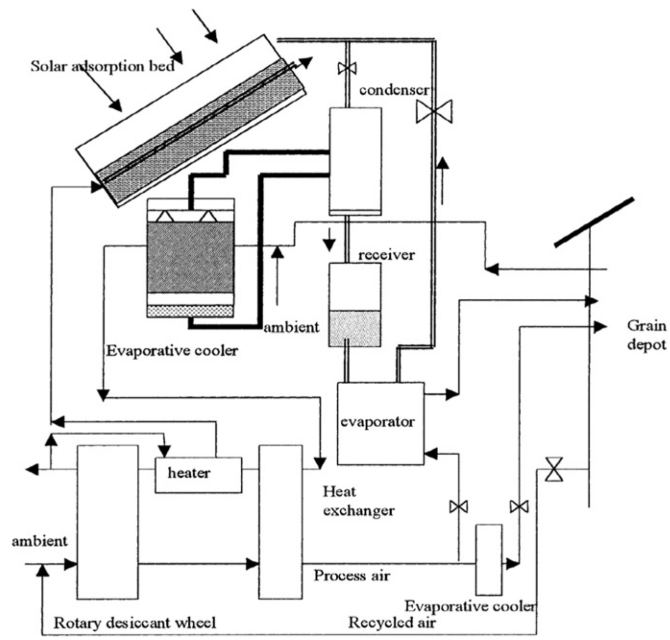


Fig. 9. Schematic of the hybrid solar adsorption–desiccant cooling system [32].

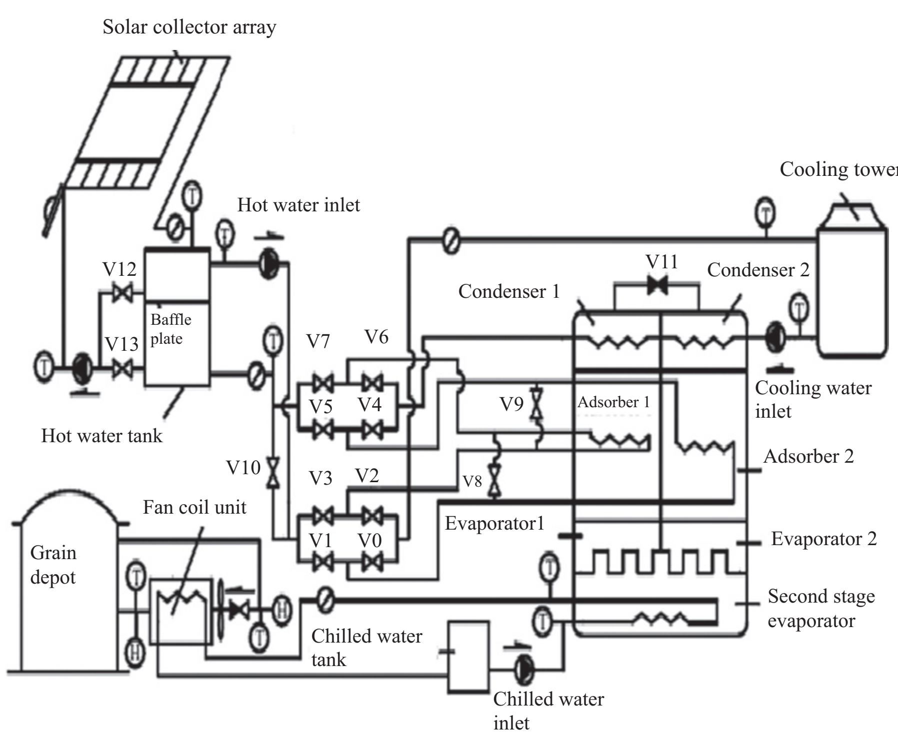


Fig. 8. Schematic diagram of the solar adsorption chiller used for grain depot cooling [31].

Moisture produced by the grain was removed by desiccant dehumidification, in which silica gel or a molecular sieve was often used as desiccant materials. The temperature of the regeneration air coming out of the rotary desiccant wheel was somewhat high, so it assisted in heating the adsorption bed with the help of auxiliary heat resources, such as burning coal or oil. The rotary desiccant wheel, together with the evaporative cooling, helped to maintain the humidity of the grain depot at a constant level that was suitable for grain storage.

Compared with the solid adsorption refrigeration system alone, the new hybrid system performs better, where the COP was about 0.4 and the outlet temperature was less than 20 °C. Hence any drawbacks of the poor efficiency of solar adsorption refrigeration and higher outlet temperature for desiccant dehumidification would be overcome. It was also found that the COP of the system increased with an increase in ambient temperature and humidity.

It was believed that the system could be used widely in the regions with abundant solar resources due to such advantages as environmental protection, energy saving and low operation costs.

Gordon et al. [33], and Saha et al. [34] proposed a novel modular and miniature chiller combined adsorption and thermoelectric cooling devices. The thermoelectric and adsorption chiller cycles is illustrated in Fig. 10. The thermoelectric junctions were separately attached to the two beds of the adsorption chiller in a thermally conductive but electrically non-conductive manner. The cold junction absorbed thermal power in driving the adsorption of refrigerant (water) onto the adsorbent (silica gel). The hot junction emitted thermal power that drives the desorption refrigerant from the adsorbent. During the heating and cooling of the beds, small on/off valves ensured no refrigerant flows into or out of the beds. After adequate heat transfer was affected, a timed controller activates the opening of the valves. Heated refrigerant from the desorber was released to a condenser for heat rejection to the environment. Vaporized refrigerant was fed to the adsorber from the evaporator which in turn cooled the load of interest.

In order to complete the cooling cycle, the roles of adsorber and desorber must be reversed. Bed switching was performed simply by reversing the polarity of the voltage V applied to the thermoelectric. What was formerly the cold junction became the hot junction and vice versa.

The performance of the system showed that the COP of the system was far larger than in conventional adsorption chillers as it reached to 0.8. For cooling load temperatures up to around 35 °C, the electro-adsorption chiller was had potential used in the cooling of machine surfaces at high heat flux. The study concluded that conventional cooling methods such as thermospyhon or convective air cooling, while functional, cannot attain comparable cooling densities of 10 W/cm^2.

Hirota et al. [35], proposed a suction-pump-assisted thermal and electrical hybrid adsorption heat pump. In this pump, a mechanical booster pump was incorporated into the thermally operated silica gel/water type adsorption heat pump for promoting water vapor transportation between an adsorber and an evaporator/condenser.

Fig. 11 shows a schematic drawing of the lab-scale hybrid adsorption heat pump system with the silica gel–water system. It was consisted of an adsorber, an evaporator/condenser, and a mechanical booster pump. The adsorber was made up of a copper

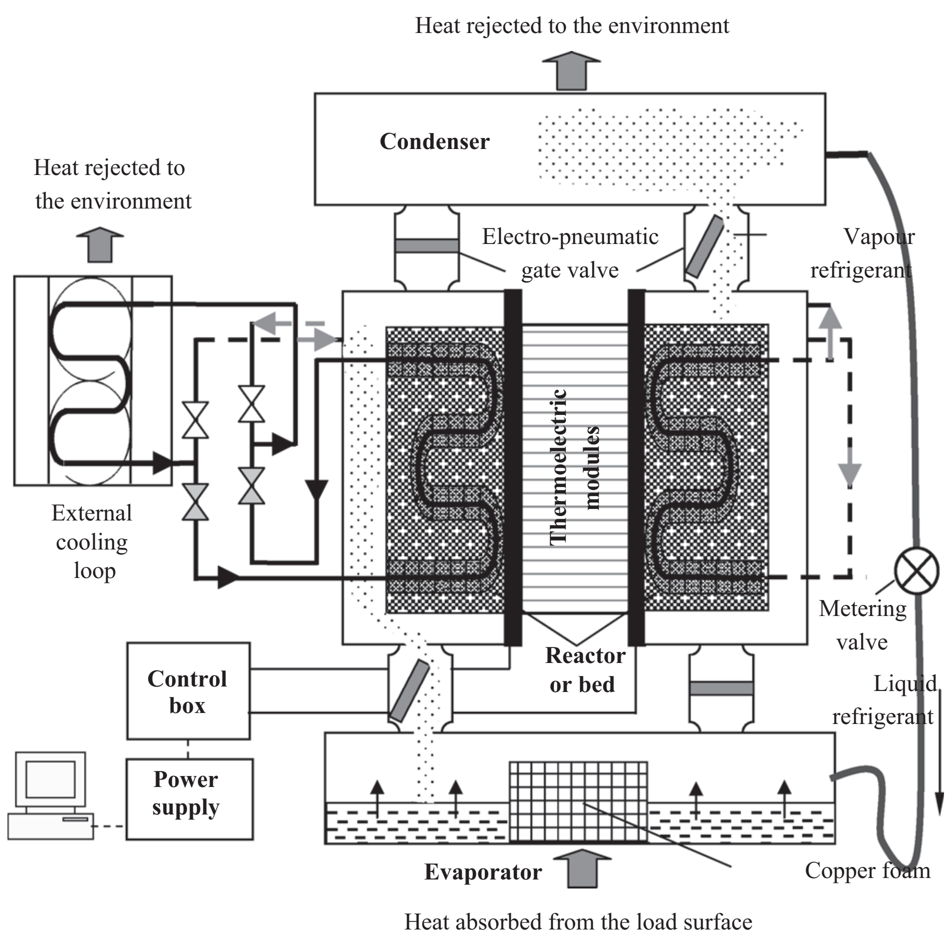


Fig. 10. Schematic for the components and energy flow of the electro-adsorption chiller [34].

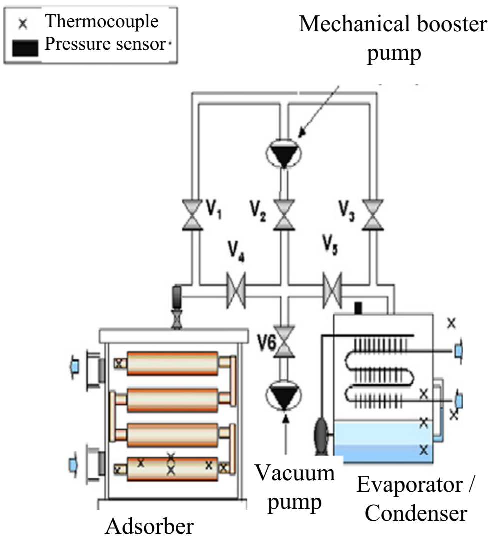


Fig. 11. Schematic of the suction-pump-assisted thermal and electrical hybrid system [35].

heat exchanger tube (I.D.: 16 mm; height: 400 mm) and copper fins cast to the tube. Silica gel with an average particle size of 412 lm was packed between the fins and wrapped by a stainless net. The mechanical booster pump was used as a suction-pump for transporting water vapor.

The effect of the mechanical booster pump power on the heat output performance of the adsorption heat pump had been studied experimentally. The suction-pump-assisted thermal and electrical hybrid adsorption heat pump was found to be able to improve the adsorptivity by approximately 1.6 times as that of the thermally operated adsorption heat pump. The hybrid adsorption heat pump was achieved a cooling power that was 1.6 times (1.032 kW) that of the thermally operated adsorption heat pump within 5 min. the COP was reached to 0.52.

Zhai et al. [36] introduced an Energy and exergy analysis on a hybrid solar heating, cooling and power generation system. The system was about a small scale hybrid solar heating, chilling and power generation system, including parabolic trough solar collector with cavity receiver, a helical screw expander and silica gel/water adsorption chiller. Fig. 12 shows a sketch diagram for the system.

The system was consisted of three main subsystems, namely, steam generation subsystem, power generation subsystem and waste heat utilization subsystem. The first subsystem included a series of parabolic trough solar collectors and an assisted gas-fired condensing boiler. A gas-fired condensing boiler had being worked as an assisted unit to ensure the steady energy input to the power generation subsystem.

The second subsystem was the power generation unit including a helical screw expander engine and a generator. With the parabolic trough collector to collect and supply the heat energy, dry saturated, superheated, even wet-saturated steam could be employed as the working fluid in the power cycle. The high-pressure working medium pushed against the vanes of a screw-type expander, converting some of its heat energy into mechanical power, turning the shaft of a generator and producing a net power output.

The third subsystem mainly consisted of two heat exchangers, a hot water tank, eight 10 kW silica gel/water adsorption chillers (in summer) and radiation heating system (in winter). The relatively high temperature exhaust steam from the helical screw expander was separated in steam separator, and dry steam flowed

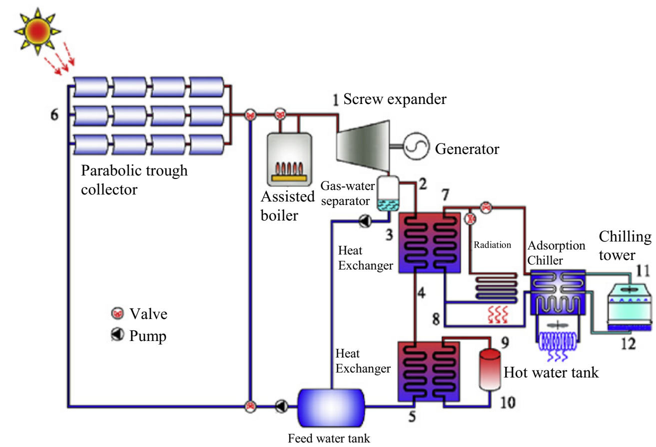


Fig. 12. Schematic of the solar heating, cooling and power generation system [36].

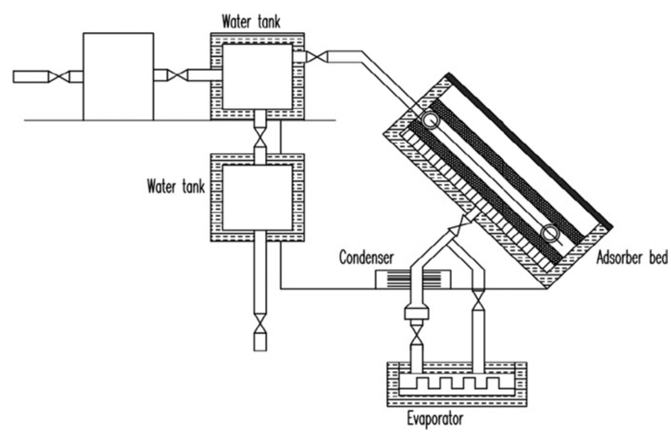


Fig. 13. Sketch of the flat plate solar hybrid system with heating and cooling solar water heater and refrigerator [37].

into the first heat exchanger. Considering that the waste heat at the temperature of 70–90 °C abounded in the exhaust steam of helical screw expander, an adsorption cooling system was chosen to offer cooling in summer.

The study concluded that, the hybrid solar system was able to produce 23.5 kW electric powers, 79.8 kW cooling with solar radiation of 600 W/m^2 and collector area of 600 m^2, and was sufficient to meet the needs from a building or a remote rural village. For the low COP of adsorption chiller, the energy and exergy destruction was the highest except those in solar collector.

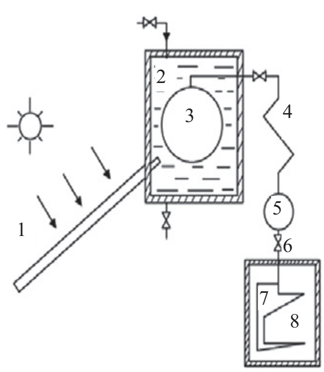
It was found that both the main energy and exergy loss was taken place at the parabolic trough collector, amount to 36.2% and 70.4%, respectively. Also it was found that the system had a higher solar energy conversion efficiency than the conventional solar thermal power generation system alone. The energy efficiency was increased to 58.0% from 10.2%, and the exergy efficiency increased to 15.2% from 12.5%.

2.2. Applications

Li et al. [37], introduced a prototype solar flat plate hybrid system with heating and cooling. Fig. 13 shows a schematic layout of the solar flat plate hybrid system. The system consisted of a combined adsorbent bed, an evaporator, a condenser, two water tanks, a reservoir, and valves, etc. The system was a

combination of two parts, the first one was conventional solar water heater and the second one represented the adsorption refrigeration system. The solar water heater collector absorber was immersed inside adsorbent bed for recovering both the sensible heat of adsorbent bed and adsorption heat.

A hybrid system of solar-powered water heater and ice-maker (Fig. 14) had been developed by Wang et al. [38,39]. The system consisted of a solar collector, water tank adsorber/generator, condenser, evaporator, receiver, ice-box, etc. The working principle was based on the combination of a solar water heater and an adsorption refrigerator. In the morning, the solar collector heated the water tank and along with the increase of water temperature, the temperature in the adsorbent bed raised. In an ideal process, the adsorbent temperature could reach a level very close to the water temperature in the tank. When the temperature in the adsorbent rose up to a temperature which caused the vapor pressure of the desorbed refrigerant up to the condensing pressure, desorbed vapor would be condensed in the condenser and collected in the receiver. This liquid refrigerant then flowed to the evaporator via a flow rate regulating valve. On the other hand the temperature of the water and the adsorbent bed continued to rise to a maximum temperature of about 80–100 °C. The high temperature water was finally drained out into a separate tank, be used more flexibly for any domestic purposes.



(1) Solar collector; (2)water tank; (3)adsorber; (4)condenser; (5)receiver; (6)valve; (7)evaporator; (8)refrigerator.

Fig. 14. Schematic of the hybrid system [38,39].

The features of the hybrid system included (1) water heating and refrigeration with one solar collector, which was suitable for household applications; (2) adsorber/generator was separated from collector, thus high efficiency vacuum collector could be used for water heating, thereby heating the adsorber at same time. Through the night, by draining the hot water from the tank, cold water was refilled to the tank, thus the adsorber was cooled and refrigeration take place.

In the sunny days, the combined adsorbent bed 9 absorbed solar radiation energy and caused the temperature of adsorbent to rise. When the temperature of adsorbent reached the desorption temperature, the adsorbent began to desorb the refrigerant. The desorbed refrigerant vapor would be condensed into liquid in the condenser 6, which was immersed into water tank 5 for good condensing results, and collected in the reservoir 4, and flowed into the evaporator 2. This process lasted until the temperature of adsorbent reached the maximum desorption temperature. In the evening, the sensible heat of adsorbent was recovered into water tank effectively by solar flat plate collector absorber immersed in the middle of adsorbent layer; this would cause the temperature of water in the tank 12 to rise. The adsorbent was cooled down efficiently due to water cooling effects whereas the water in tank 12 was heated. When the temperature of water in the tank 12 reached to an expected temperature, such as 45 °C, water valve 16 was opened, this yielded water in the tank 12 flowed into water tank 17. If water valve 13 was opened, the city water will flew into water tank 12 to cool the adsorbent bed again. When the refrigerant pressure in adsorbent bed reached evaporating pressure, valves 3 and 7 were opened, and the adsorbent would begin to adsorb the refrigerant from the evaporator 2. The cooling effect was got from refrigerant evaporation, and the ice was formed in the thermal insulated water box 1.

The Experiments showed that approximately 5–6 kg of ice per m^2 of collector could be produced each day under the condition of 18–22 MJ/m^2 solar radiation, mean while 60 kg of hot water at 45–50 °C could be provided for residential use. The study concluded that the hybrid machine would be of high efficiency of solar energy conversion as the COP was 0.11, it would be a good choice for the utilization of solar energy.

Wang et al. [40], installed an experimental prototype of a combined adsorption heating and cooling system. The system consisted of a heater, a water bath, an activated carbon/methanol adsorption bed and an ice box. The system was just a combination of solar water heater and solar adsorption ice maker, shown in Fig. 15.

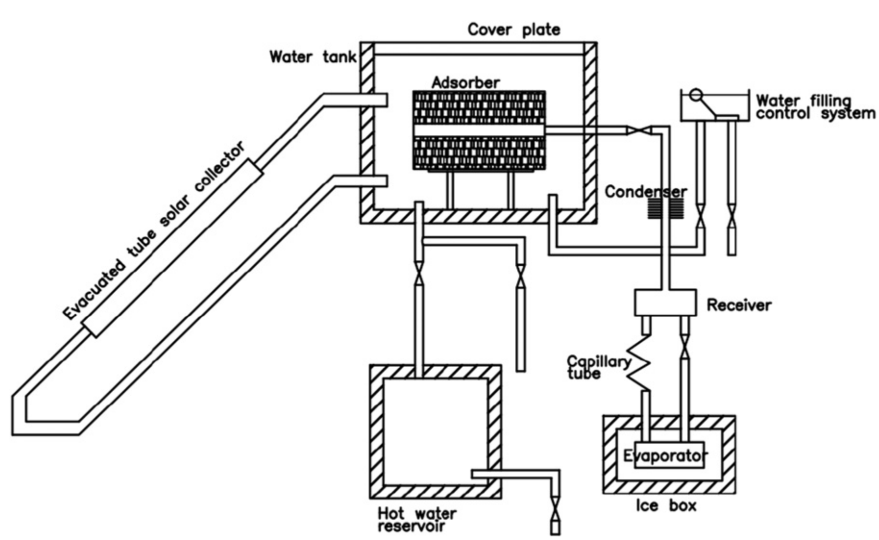


Fig. 15. Schematics of a solar water heater and adsorption refrigerator [40].

When 55 MJ heating was added to 120 kg of water at 21 °C, and the condensing temperature was controlled at about 30 °C, the result was the 4 kg water contained inside the methanol refrigerant evaporator was iced to −2 °C, the cooling capacity of the ice and the refrigerant in the evaporator was maintained the 100 L cold box for about three days below 5 °C. This research showed that the hybrid solar water heating and ice making was reasonable, and the combined cycle of heating and cooling was meaningful for real applications of adsorption systems.

A novel micro combined cooling, heating and power adsorption system, which was based on a two bed silica gel/water adsorption chiller, was constructed by Li and Wu [41]. To reveal the chiller characteristic of the system, a transient model of the adsorption chiller was developed.

Fig. 16 shows the schematic diagram of the micro CCHP system. The system comprised one gas engine generator set with 16 kW generating capacities, two bed silica gel/water adsorption chiller with 10 kW cooling capacity, one exhaust heat exchanger, 500 L water tank, and three pumps.

It was found that the cooling capacity and the COP of the chiller were influenced significantly by the average value and variation rate of electric load, as well as the average value of cooling load. The water tank also showed a great effect on the chiller performance. A 500 L water tank was recommended in order to get better performance and acceptable start-up time. The COP of the system was reached to 0.44 with a cooling load of 7.9 kW.

Chang et al. [42] designed and constructed a solar-powered adsorption compound system for heating and cooling. A schematic diagram for the whole system is shown in Fig. 17. An integrated, two-bed, closed-type adsorption chiller was developed. Plate fin and tube heat exchangers were adopted as an adsorber and evaporator/condenser.

Under the test conditions of 80 °C hot water, 30 °C cooling water, and 14 °C chilled water inlet temperatures, a cooling power of 9 kW and a COP of 0.37 was achieved. It had provided a SCP (specific cooling power) of about 72 W/kg. The efficiency of the collector field lied in 18.5–32.4%, with an average value of 27.3%. The daily average COP of the adsorption chiller lied in 33.8–49.7%, with an average COP of 40.3% and an average cooling power of 7.79 kW. A typical daily operation showed that the efficiency of the solar heating system, the adsorption cooling and the entirely solar cooling system was 28.4%, 45.2%, and 12.8%, respectively.

Clausse et al. [43] performed a residential air conditioning and heating by means of enhanced solar collectors coupled to an adsorption system. For air-conditioning, enhanced compound parabolic solar collectors were used as a heat source of an adsorption system (activated carbon/methanol) while during winter; direct coupling with the building was performed. A model describing the adsorption unit, the solar collectors and the house was used to simulate the performances of such an installation.

The complete system layout is illustrated in Fig. 18. It included the solar system, the adsorption machine and the floor heating/cooling system. All sub-systems were directly connected to each other without storage or control system to regulate the temperature. To calculate the performances of the installation, a numerical model of the solar panels, the adsorption unit and the house was developed.

For air-conditioning, thermal comfort was achieved as indoor temperature was kept below 25 °C during five consecutive hot days, contrarily to the case for which only free-cooling during night time was used. For heating, the indoor temperature remained below the comfort temperature value by 2 °C. The COP of the cycle was about 0.2 and the cooling capacity was reached to 4.6 kW.

Kong et al. [44,45] and Wang and Oliveira [46] studied the experimental investigation of a micro-combined cooling, heating and power system driven by a gas engine. A natural gas and LPG-fired micro-combined cooling, heating and power system used a small-scale generator set driven by a gas engine and a new small scale adsorption chiller, which had a rated electricity power of 12 kW, a rated cooling of 9 kW and a rated heating capacity of 28 kW. Silica gel/water was used as the working pair in the adsorption cooling system. The main components of a cogeneration system were the prime mover generator set, heat recovery

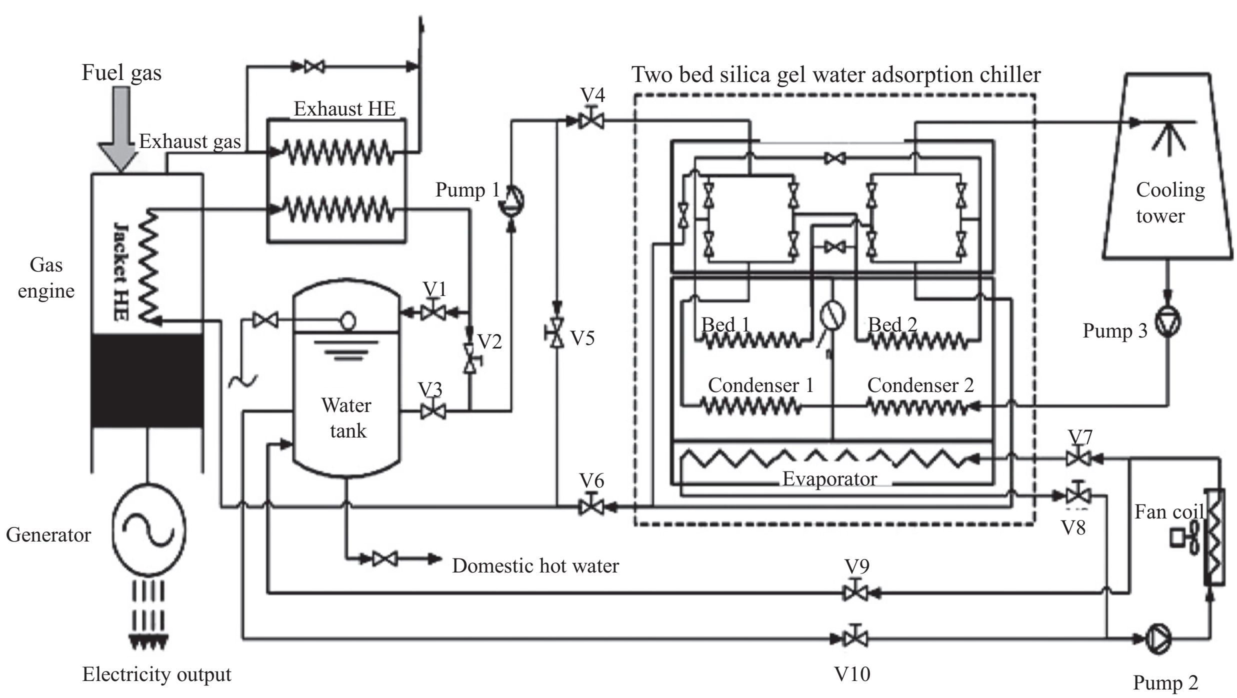


Fig. 16. Schematic diagram of the micro combined cooling heating and power system [41].

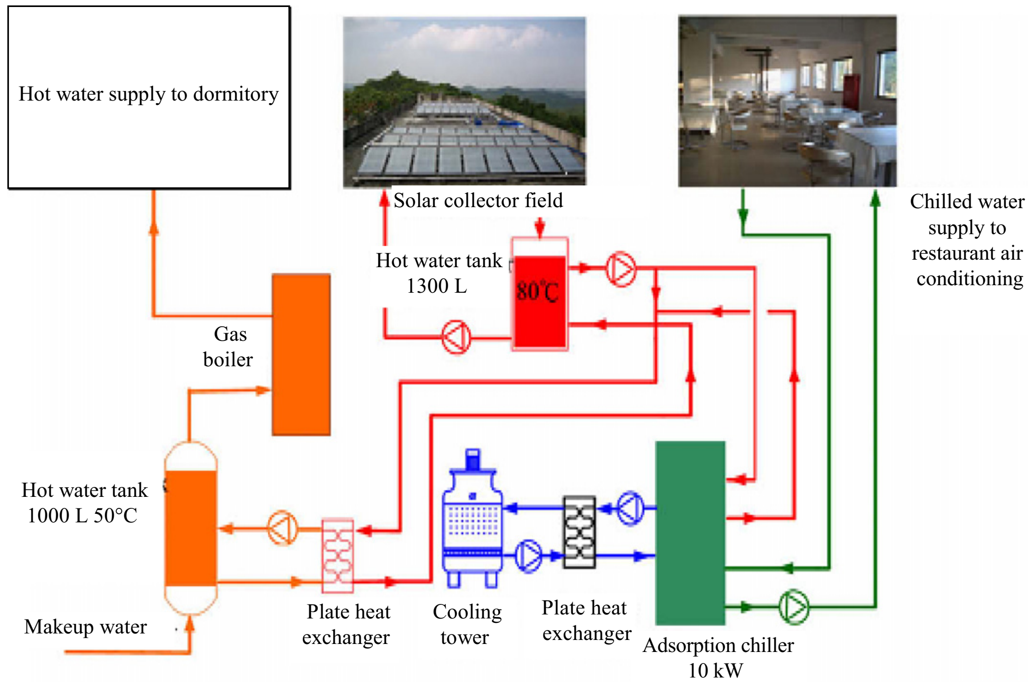


Fig. 17. Schematic diagram of the solar-powered system for heating and cooling [42].

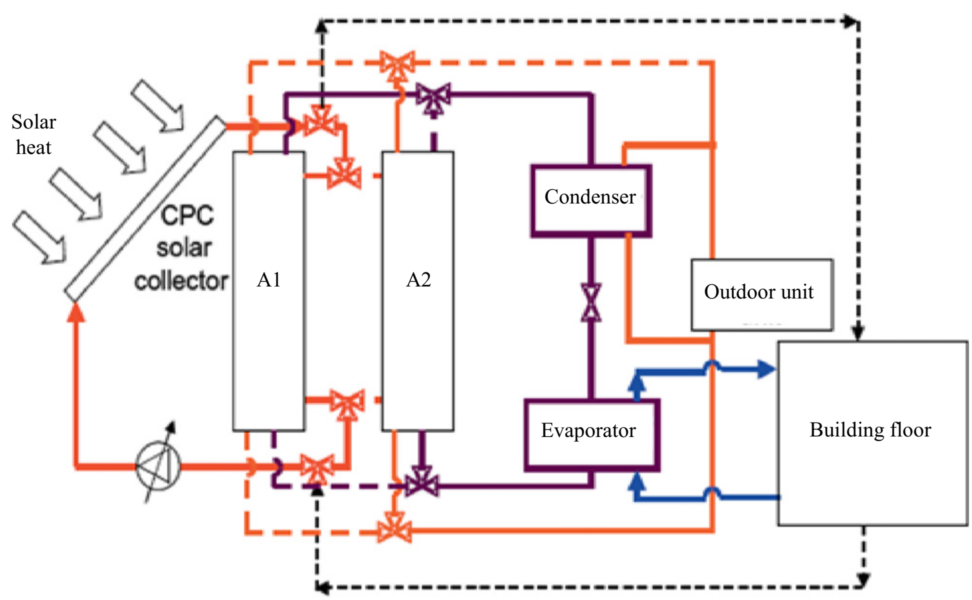


Fig. 18. Solar cooling adsorption installation sketch [43].

equipment, control equipment, and electrical transmission and distribution system. Fig. 19 shows a photograph for the adsorption cooling system. The COP of the chiller was over 0.3 for 13 °C evaporation temperature. An energetic analysis of micro-cooling heating and power system was performed as well. The overall thermal and electrical efficiency was over 70%.

2.3. Heat source

Waste heat, especially for the low grade would be the best driving heat source for adsorption refrigeration systems. A large amount of waste heat yields in the process of production in chemical plants, power stations, steel plants, engines in automobiles and so on. Because of no corrosions, no crystallization and more fitting for the utilization in moving and vibrating situations, the adsorption refrigeration would be a more competitive candidate than the absorption refrigeration. However, the adsorption refrigeration has not been used in regeneration of waste heat on a large scale because of some technical problems. Only some adsorption prototypes [47,48,49,50] driven by waste heat are developed for demonstration applications. So built a hybrid adsorption cooling system to use the waste heat may be more convenient up to now.

Oertel and Fischer [51] introduced a hybrid adsorption cooling system for cold storage using silica gel/methanol. For the cold storage of agricultural products at temperatures of 2–4 °C, a solar hybrid cooling system had been developed, using solar energy from flat plate collectors and the waste heat of a genset, operated

Fig. 19. Silica gel/water adsorption chiller [44,45].

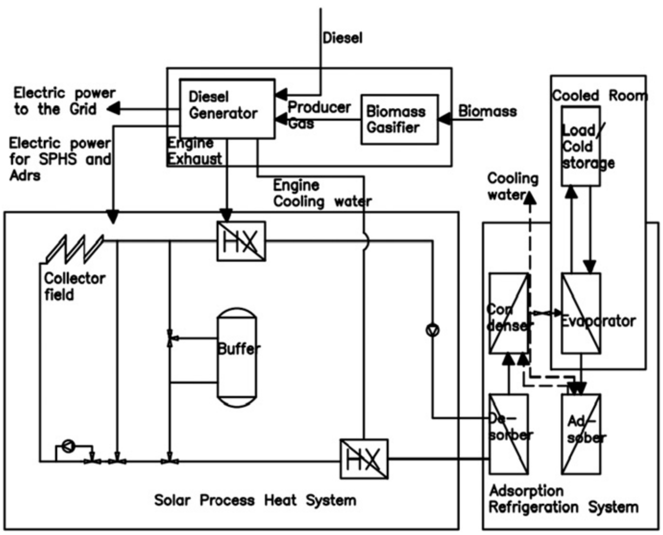


Fig. 20. Draft system design for solar-hybrid adsorption cold storage [51].

with producer gas. A commercially available low temperature (80–90 °C) adsorption cooling system for air conditioning application was modified to operate with methanol instead of water as a refrigerant.

The developed system is shown in Fig. 20. The system was built up with a condenser, a throttle valve, an evaporator and the sorption chamber as thermal compressor. The thermal compressor was operated in two phases (adsorption and desorption). The heat of adsorption, which was set free, was removed by a heat exchanger in the reaction chamber with the cooling water. After saturation of the silica gel the adsorbent was regenerated by an isosteric heating of the adsorbent.

The maximum capacity of the components of the system was about 2 kW. Experiments and calculations showed that the COP for a commercial adsorption cooling system reduced about 70% when operating the system with silica gel/methanol at a chilled water temperature of −2 °C, a heating water temperature of 85 °C and a condenser temperature of 30 °C. The COP was reached to 0.5 with methanol and 0.65 with water.

Habib et al. [52,53] introduced a Study on solar driven combined adsorption refrigeration cycles in tropical climate. This novel cycle amalgamated the activated carbon/R507A as the bottoming cycle and activated carbon/R134a cycle as the topping cycle and deliver refrigeration load as low as 10 °C at the bottoming cycle.

As shown in Fig. 21, the combined cycle was powered by solar heat using the meteorological data of Singapore and Malaysia. The R507A cycle comprised an evaporator, a condenser and two sorption elements (SEs) and the R134a cycle consisted of an evaporator, a condenser and two sorption elements (SEs). The condenser of the R507A cycle was linked with the evaporator of the R134a cycle in the same shell and coil heat exchanger where shell side referred to the evaporator of R134a cycle and coil side represented the condenser of R507A cycle. Only heat was transferred between the heat exchanger, so that the evaporator of the R134a cycle took cooling load from the condenser of the R507A cycle. It should be noted here that there was no mass transfer between them, and the working principle of the R134a cycle was same as the R507A cycle. Due to cooling load effects, the combined cycles started from the AC-R507A cycle. The evaporated refrigerant in the R507A cycle was adsorbed onto the adsorbent and stored in the cold bed or the adsorber.

A simulation program had been developed for modeling and performance evaluation for the solar driven combined adsorption refrigeration cycle using the meteorological data of Singapore and Malaysia. Simulation results showed that from 10am to 5pm the maximum heat input could be provided to the combined cycle. This novel combined cycle could deliver refrigeration load at −10 °C, where the COP could be reached to 0.15. It could be concluded that, the cycle could be useful for freezing applications.

Li et al. [54] analyzed the performance of a multi-mode thermochemical sorption refrigeration system for solar powered cooling. The proposed system consisted of three sorption refrigeration cycles that can be operated based on the solar energy insolation: combined double way cycle, double effect cycle and two stage cycles. The multi-mode sorption refrigeration system is shown in Fig. 22. The working performance of the different sorption cycles were theoretically analyzed and compared. For combined double way sorption cycle, both adsorption refrigeration and resorption refrigeration were combined to improve the cooling capacity. For double-effect sorption cycle, one internal heat recovery process was employed to enhance the energy utilization efficiency. For two stage cycle with internal heat recovery process, a secondary reactive salt was used to lower the driving regeneration temperature. The multi-mode system achieved a COP of about 0.9 in case of using double way sorption cycle.

Koyama et al. [55] introduced an invented hybrid adsorption cooling system using activated carbon/CO_2 pair. The system used heat from car engine as a heat source to drive the adsorption bed with a vapor compressor. The system consisted of a compressor, a gas cooler, an expansion device and an evaporator as shown schematically in Fig. 23. The system achieved a very high a COP which yielded about 4 at high pressure of 9.5 MPa for gas cooler of 35 °C.

3. Summary

To make a good picture for the collected data about the hybrid adsorption cooling systems a summary table has been introduced (Table 1). The table arranged the systems according the used technology in its operation. The comparing data are system technology, adsorbent-refrigerant pairs and the COP of the surveyed systems.

4. Conclusions

An overview of hybrid adsorption cooling systems has been conducted in order to see the present status and future trend. The survey sectioned the hybrid systems into three categories

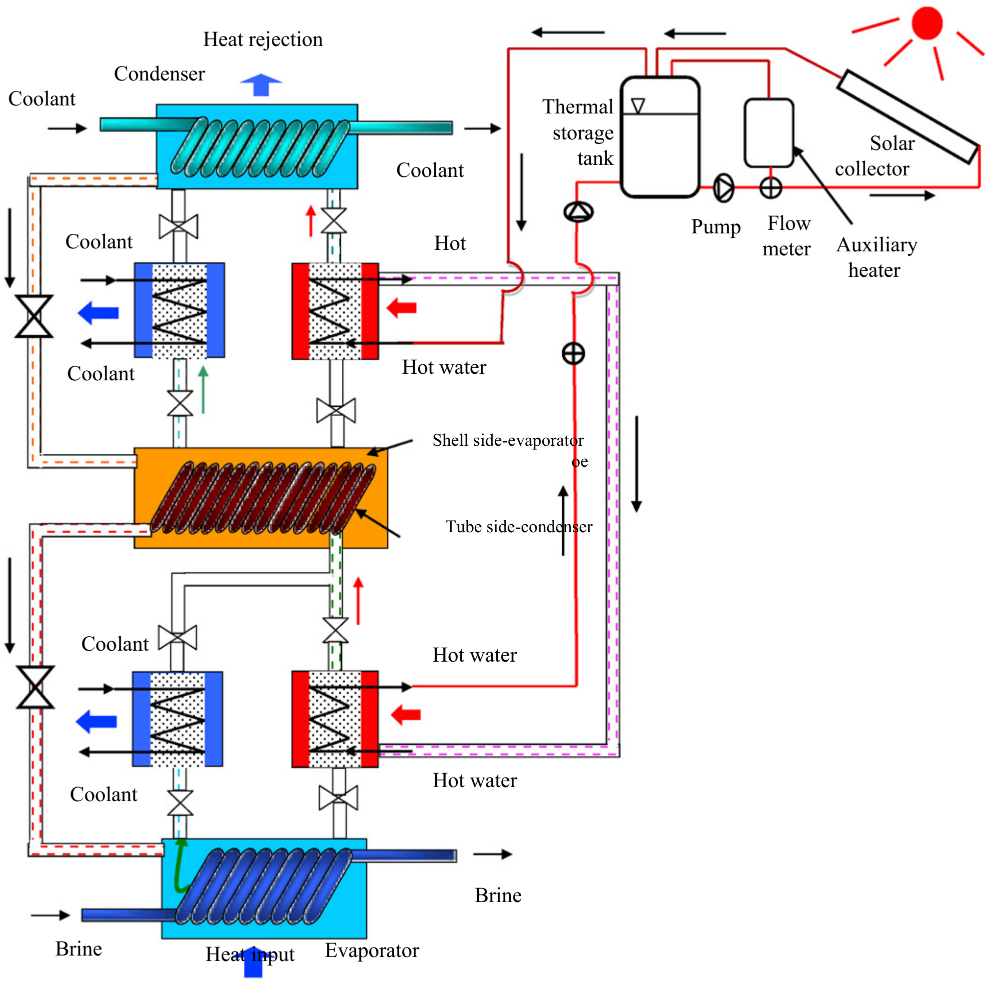


Fig. 21. Schematic diagram of combined adsorption refrigeration cycle [52].

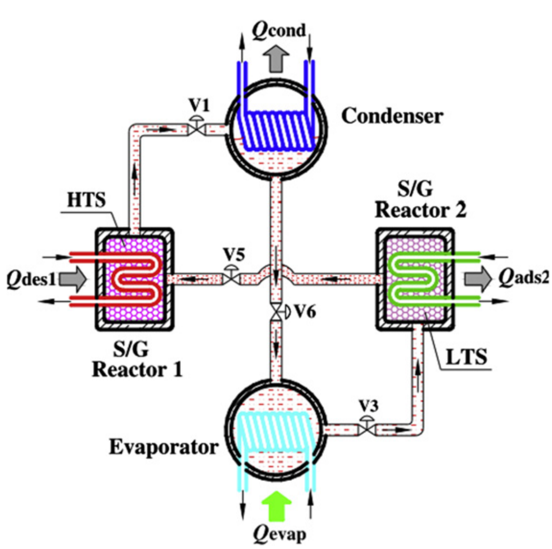


Fig. 22. Combined double-way sorption refrigeration cycle [54].

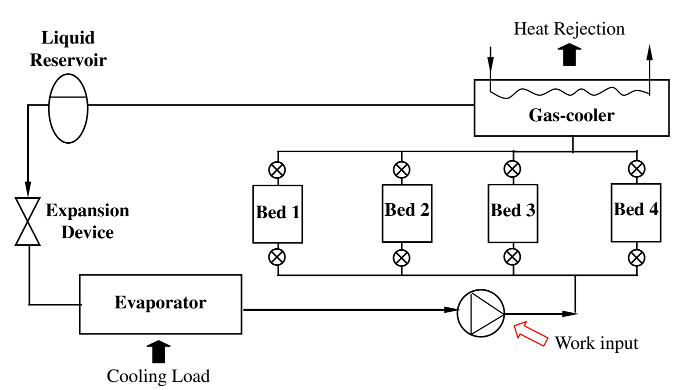


Fig. 23. Activated carbon/CO_2 based hybrid compression adsorption cycle [55].

based on (i) assisted technology used beside the adsorption cycle (ii) application of the hybrid system, and (iii) heat source type.

The main findings are:

- A few studies were done using different heat sources to drive the adsorption cycles.
- Adsorption cycle employing silica gel/water pair was found to achieve the highest values of COP for low pressure applications.
- The invented hybrid system using AC/CO_2 has the highest COP for high pressure applications.
- The minimum value of the COP was found to be with the system which uses activated carbon/R134a as the adsorbent/refrigerant pair.
- The COP values are lower for systems employing activated carbon/methanol pair than those of silica gel/water based systems.

Table 1
Hybrid adsorption cooling systems.

System type	Adsorbent/refrige-rant pair	Cooling COP
Assistant technology		
Ads./vapor comp./liquid desiccant [24]	Silica gel/water	2.8
Ads./vapor compression [25]	AC/R134a	0.1
Ads./vapor compression [26]	Silica gel/water	0.59
Ads./ejector [28]	Zeolite/water	0.1–0.23
Ads./ejector [29]	Zeolite/water	0.43
Ads./grain depot [31]	Silica gel/water	0.1-0.13
Ads./desiccant wheel [32]	Silica gel/water	0.4
Ads./thermoelectric cooling [33]	Silica gel/water	0.8
Ads./suction pump [35]	Silica gel/water	0.52
Ads./helical screw expander [36]	Silica gel/water	0.44
Application		
Ads. cooling/heating [37]	AC/methanol	0.11
Ads. cooling/h'eating [40]	AC/methanol	0.14
Ads. cooling/heating and power [41]	Silica gel/water	0.44
Ads. cooling/heating [42]	Silica gel/water	0.41
Ads. cooling/heating [43]	AC/methanol	0.2
Ads. cooling/heating [44]	Silica gel/water	0.3
Heat source		
Ads./solar/ waste heat [51]	Silica gel/methanol	0.5
Ads./solar/ waste heat [51]	Silica gel/water	0.65
Combined adsorption cycle [52]	AC/R134a, AC/507a	0.15
Multi-mode sorption cycle [54]	$MnCl_2$–NaBr–NH_3	0.9
Ads./car engine/ vapor compressor [55]	AC/CO_2	4

- The thermoelectric cooling technology achieves higher COP value than the other technologies when using it as an assisted technology with the adsorption chiller.
- Adsorption cooling systems with mixed heat sources are promising.

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